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MILLIHERTZ OPTICAL/UV OSCILLATIONS IN 4U 1626–67: EVIDENCE FOR A WARPED ACCRETION DISK[1]

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ABSTRACT

We have detected large-amplitude 0.3–1.2 mHz quasi-periodic oscillations (QPOs) from the low-mass X-ray binary pulsar 4U 1626–67/KZ TrA, using ultraviolet photometry from the *Hubble Space Telescope* and ground-based optical photometry. These 1 mHz QPOs, which have coherence $(\nu/\Delta\nu) \approx 8$, are entirely distinct from the 130 mHz pulsar spin frequency, a previously known 48 mHz QPO, and the 42 min binary period (independently confirmed here). Unlike the 48 mHz and 130 mHz oscillations which are present in both the optical/UV and the X-ray emission, the 1 mHz QPOs are not detected in simultaneous observations with the *Rossi X-Ray Timing Explorer*. The rms amplitude of the mHz QPO decreases from 15% in the far UV to 3% in the optical, while the upper limit on a corresponding X-ray QPO is as low as $< 0.8\%$. We suggest that the mHz oscillations are due to warping of the inner accretion disk. We also report the detection of coherent upper and lower sidebands of the 130 mHz optical pulsations, with unequal amplitude and a spacing of 1.93 mHz around the main pulsation. The origin of these sidebands remains unclear.

Subject headings: accretion, accretion disks — binaries: close — pulsars: individual: 4U 1626–67 — stars: individual: KZ TrA — stars: low-mass — stars: neutron

1. INTRODUCTION

The optical and ultraviolet emission from low-mass X-ray binaries (LMXBs) is primarily powered by irradiation of the accretion disk and/or the mass donor by the central X-ray source. In short period binaries, this reprocessed emission generally dominates both the internal (viscous) heating in the disk (except perhaps at the smallest disk radii) and the intrinsic luminosity of the donor star (see van Paradijs & McClintock 1995 for a review). Since the time history of the optical/UV emission should thus be a convolution of the X-ray intensity history with a function representing the binary and disk geometry, we expect that periodic or quasi-periodic modulation of the optical/UV emission should arise from one of only two causes: (1) a similarly modulated "input" X-ray intensity, as in coherent X-ray pulsations or quasi-periodic oscillations (QPOs) (see, e.g., Chakrabarty 1998); and (2) orbitally-modulated X-ray heating of the binary companion's surface (see van Paradijs & McClintock 1995). In this paper, we present evidence that a third mechanism must exist, and suggest implications for the smoothness of the accretion disk surface in LMXBs.

The LMXB 4U 1626–67 consists of a 7.66 s X-ray pulsar accreting from an extremely low-mass ($\lesssim 0.1 M_\odot$) companion in an ultracompact 42 min orbit (Middleditch et al. 1981; Levine et al. 1988; Chakrabarty 1998). The 130 mHz (=1/7.66 s) X-ray pulsations arise from anisotropic accretion of matter on the surface of a rotating, highly-magnetized neutron star whose spin and magnetic dipole axes are misaligned. A 48 mHz QPO is detected in the X-ray emission (Shinoda et al. 1990; Kommers, Chakrabarty, & Lewin 1998), and probably arises via an interaction between the pulsar's magnetosphere and the accretion disk.

The optical counterpart, KZ Triangulum Australis (KZ TrA), has a strong ultraviolet excess (McClintock et al. 1977), and optical pulsations are detected at the same 130 mHz frequency as the X-ray pulsations (Ilovaisky et al. 1978). The pulsed optical emission from the system is understood as primarily due to X-ray reprocessing in the accretion disk (Chester 1979; McClintock et al. 1980; Chakrabarty 1998). The power spectral peak of the optical pulsations has a weak but persistent lower-frequency sideband ($\Delta\nu$ =0.4 mHz) which has been interpreted as due to X-ray reprocessing on the surface of a companion star in a 42-min prograde binary orbit (Middleditch et al. 1981; Chakrabarty 1998). In addition, the 48 mHz QPO detected in the X-ray emission is also detected in the optical band (Chakrabarty 1998). During the 1970s and 1980s, the system also showed strong, correlated X-ray/optical flares every $\sim$1000 s that are of undetermined origin (Joss, Avni, & Rappaport 1978; McClintock et al. 1980; Li et al. 1980).

Overall, the known time variability of the optical emission

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TABLE 1
LOG OF OPTICAL AND ULTRAVIOLET OBSERVATIONS

Start Time (UT)	Duration (hr)	Obs.	Time res.	Bandpass[a]	Millihertz QPO Centroid (mHz)	FWHM (mHz)	Amplitude (% frac. rms)
1996 Jun 18, 18:40	1.9	SAAO	10 s	Optical	0.46	0.15	4.7
1996 Jun 19, 21:38	0.9	SAAO	10 s	Optical	1.02	0.33	3.8
1996 Jun 21, 19:53	2.8	SAAO	10 s	Optical	1.13	0.10	4.6
1998 Apr 23, 05:56	2.3	*HST*	125 μs	NUV	1.16	0.31	3.4
1998 Apr 23, 09:11	2.3	*HST*	125 μs	FUV	0.74	0.70	15.1
1998 Jun 25, 17:39	0.8	SAAO	5 s	Optical	1.18	0.31	3.3
1998 Jun 27, 18:51	8.1	SAAO	2 s	Optical	1.19	0.15	4.4
1998 Jun 28, 17:15	2.0	SAAO	2 s	Optical	1.15	0.12	3.4
1998 Jun 29, 17:07	2.2	SAAO	2 s	Optical	0.33/1.03	0.15/0.14	4.3/3.8

[a]Optical=white light; NUV=1650–3100 Å; FUV=1150–1700 Å.

from 4U 1626–67 is closely correlated with the X-ray emission. In this paper, however, we report on the discovery of two previously unknown timing features in the emission from 4U 1626–67: a strong 0.3–1.2 mHz quasi-periodic modulation in the optical and ultraviolet emission, and lower and upper sidebands of the coherent pulsations with symmetric separation from the main peak ($\Delta\nu$ = 1.93 mHz) but asymmetric strengths. These new modulations are absent in simultaneous X-ray data.

2. OBSERVATIONS

2.1. *Ultraviolet observations*

Our *Hubble Space Telescope (HST)* observations of KZ TrA were made on 1998 April 23 using the Space Telescope Imaging Spectrograph (STIS; Kimble et al. 1998). A log of the observations is given in Table 1. Two *HST* orbits (P = 96 min) of data were acquired using the Cs_2Te multi-anode microchannel array (MAMA) detector (STIS/NUV-MAMA), which operates in the near ultraviolet band (NUV; 1650–3100 Å). Another two orbits of data were acquired using the solar-blind CsI MAMA (STIS/FUV-MAMA), which operates in the far ultraviolet band (FUV; 1150–1700 Å). Useful data were obtained for about 45 min of each 96 min *HST* orbit. The remainder of each orbit was occupied by guide star acquisition, instrumental calibration and readout overheads, and Earth occultations of the source.

Our observations were acquired in a backup guiding mode using only a single guide star, because one of the *HST* Fine Guidance Sensors was unable to achieve fine lock on its guide star. The telescope pitch/yaw angles were controlled using the one available guide star, and the roll angle by gyroscope. Both the STIS initial target acquisition and 5-point linear peakup procedure succeeded normally. The small drifts in roll angle that might have occurred in this gyroscope mode could not give rise to a mHz QPO signal of the strength that we are reporting in this paper (and which are also seen independently in our ground-based optical data[4]).

Both STIS MAMA cameras were operated in TIMETAG mode, which records both the detector coordinate and the arrival time (Δt = 16μs) of each detected photon individually. The observations were made through a 52$\times$0.2 arcsec^2 long slit and a low-resolution grating (G230L for the NUV observation and G140L for the FUV observation) in order to obtain spectral information as well. However, for the analysis presented here, we summed the spectra along the dispersion axis in order to obtain broad-band photometry over the entire bandpass of each camera. The complete NUV and FUV light curves are shown in the top two panels of Figure 1. A spectroscopic analysis will be reported separately (Wang & Chakrabarty 2001).

2.2. *Optical observations*

We observed a small (50$\times$33 arcsec^2) region surrounding KZ TrA using the UCT-CCD fast photometer (O'Donoghue 1995) at the Cassegrain focus of the 1.9-m telescope at the South African Astronomical Observatory (SAAO) in Sutherland, South Africa, on 1996 June 19–22 and on 1998 June 25–30. A detailed observation log is given in Table 1. The UCT-CCD fast photometer is a Wright Camera 576$\times$420 coated GEC CCD, which was used half-masked and operated in frame-transfer mode, allowing exposures as short as 1 s with no dead time. Unlike photoelectric aperture photometry, the CCD images automatically provide a simultaneous sky background measurement over the entire observation.

The 1996 observations were taken at 10 s resolution, and the 1998 observations were taken at either 2 s or 5 s resolution. All the observations were taken in white light with no bandpass filters in place. The data reduction procedure is described by Homer, Charles, & O'Donoghue (1998). A preliminary analysis of the 1996 observations was presented by Homer (1998). An excerpt of the light curve from the 1998 June 29 observation is shown in the bottom panel of Figure 1.

2.3. *X-ray observations*

For both the 1998 April *HST* and the 1998 June SAAO observations, coordinated simultaneous X-ray observations were made using the *Rossi X-Ray Timing Explorer (RXTE)*. A log of these observations is given in Table 2. The analysis presented here uses data from the *RXTE* Proportional Counter

[4] Indeed, additional *HST*/STIS data of the source taken in 1999 also contain these mHz oscillations.

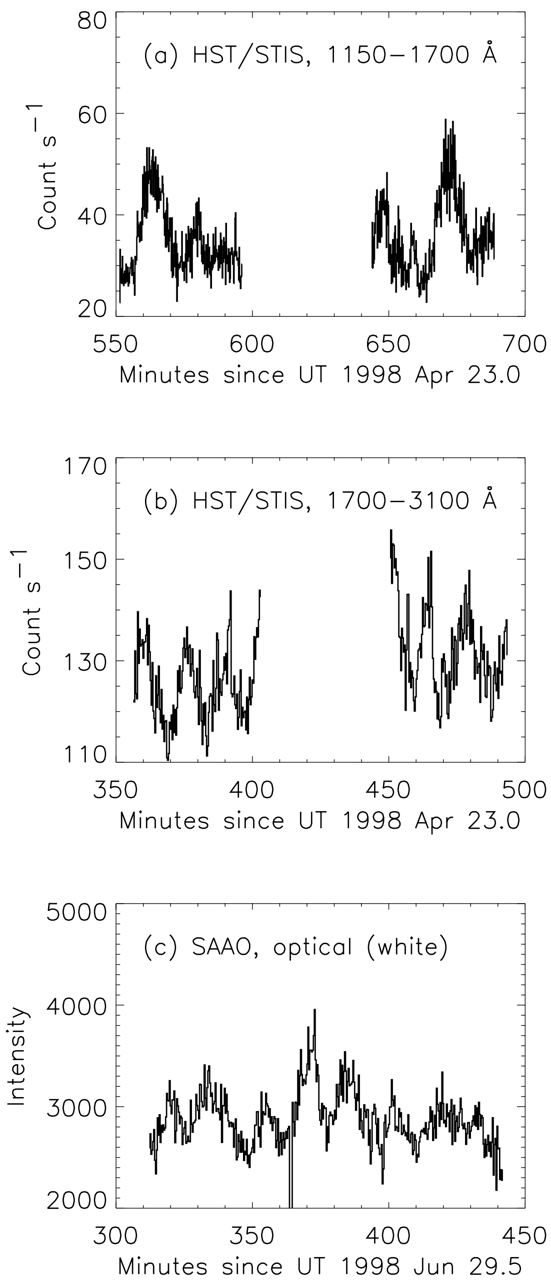

FIG. 1.— UV and optical light curves of 4U 1626–67/KZ TrA. (a) Far-UV (1150–1700 Å) *HST*/STIS light curve from 1998 Apr 23. (b) Nearr-UV (1700–3100 Å) *HST*/STIS light curve from 1998 Apr 23. (c) Optical (white light) light curve from 1998 June 29.

Array (PCA; Jahoda et al. 1996), which operates in the 2–60 keV range with a total effective area of $\sim$6500 cm^2 and a collimated 1° field of view. The PCA data were recorded in a variety of different data modes simultaneously. For our analysis, we used the `Standard1` data (0.125 s time resolution, no energy resolution) and the `Standard2` data (16 s time resolution, 128 channel energy resolution).

During the 1998 April observations, 4U 1626–67 was in the continuous viewing zone (near the orbital pole) of *RXTE*, so that it was never subject to Earth occultation. This allowed unusually long uninterrupted observations. The short gaps between these observations were due to spacecraft passages through the South Atlantic Anomaly (SAA; a region of extremely high

TABLE 2
LOG OF *RXTE* OBSERVATIONS

Start Time (UT)	Obs. ID	Duration (hr)
1998 Apr 23, 01:24	30058-01-01-00	7.0
1998 Apr 23, 08:45	30058-01-01-00	5.4
1998 Apr 23, 10:32	30058-01-01-00	1.1
1998 Jun 25, 17:39	30060-01-01-04	1.2
1998 Jun 27, 17:41	30060-01-01-03	1.1
1998 Jun 27, 19:17	30060-01-01-01	2.7
1998 Jun 28, 17:41	30060-01-01-06	1.1
1998 Jun 29, 17:40	30060-01-01-07	1.1

particle background in the Earth's magnetosphere) during which the detector high-voltage was turned off. The 1998 June observations were subject to both Earth occultations and SAA passages, and thus contain gaps.

3. ANALYSIS AND RESULTS

There were a variety of oscillations present in our data, both quasi-periodic and periodic, some previously known and some reported here for the first time. In order to make a quantitative analysis of the timing properties of these data, we computed the Fourier power spectrum for each observation. We adopted the root-mean-squared (rms) normalization convention widely used in the QPO literature (e.g., Miyamoto et al. 1994; van der Klis 1995). Unlike simple photon-counting data, the measurement noise in our data contains additional contributions beyond counting statistics. Nevertheless, we found that the overall measurement noise in our CCD data is well-described by a Gaussian white noise process, and we simply estimated the white noise level from the high-frequency ($>$ 100 mHz) power spectrum of the data and subtracted it off, as with the Poisson noise case for photon counting data. Table 3 summarizes the amplitudes of the 1 mHz and 48 mHz QPOs, and Table 4 summarizes the pulsed amplitude of the coherent pulsations.

3.1. *1 mHz QPO*

All the optical and ultraviolet data sets showed a clear $\sim$1 mHz modulation in intensity. There is no previously known QPO at this frequency from 4U 1626–67, although bright X-ray and optical flaring on 1000 s time scales has been seen (see §4). As shown in Figure 1, individual cycles of this modulation are clearly visible in the data. The centroid frequency of the modulation was always around 1 mHz, although values as low as 0.46 mHz and as high as 1.19 mHz were observed. On 1998 June 29, a pair of distinct modulations of comparable amplitude was detected with centroid frequencies of 0.33 mHz and 1.03 mHz. A summary of the measured QPO frequencies, widths, and amplitudes is given in Table 1.

In the longest observations, the 1 mHz modulation was resolved in the power spectrum and had a coherence $Q \equiv \nu/\Delta\nu$ in the range of 8–11. A power spectrum of the longest optical observation is shown in Figure 2. The limited frequency resolution of the shorter observations yielded only lower limits for Q which are consistent with this range. The root-mean-squared (rms) fractional amplitude of the modulation was in the 3–5% range for the optical and NUV observations and over 15% for the FUV data.

TABLE 3
FRACTIONAL RMS AMPLITUDE OF QPO FEATURES

Date	Band	∼1 mHz QPO (%)	48 mHz QPO (%)
1996 Jun 18	Optical	4.7	> 3.2
1996 Jun 19	Optical	3.8	> 2.3
1996 Jun 21	Optical	4.6	> 2.6
1998 Apr 23	NUV	3.4	2.6
1998 Apr 23	FUV	15.1	6.3
1998 Apr 23	X-ray	< 3.7	13.9
1998 Jun 25	Optical	3.3	3.2
1998 Jun 25	X-ray	3.9?	12.2
1998 Jun 27	Optical	4.4	4.0
1998 Jun 27	X-ray	< 2.4	13.5
1998 Jun 28	Optical	3.4	3.9
1998 Jun 28	X-ray	< 0.8	15.0
1998 Jun 29	Optical	4.3/3.8	4.0
1998 Jun 29	X-ray	4.9?/4.8?	13.1

No 1 mHz modulation was detected in simultaneous X-ray observations in 1998 April and June, with 3σ upper limits ranging from $< 0.8\%$ to $< 5\%$. A power spectrum of the longest X-ray observation (which provided the most stringent upper limit) is shown in Figure 3. A comparison of the mHz QPO amplitude in the different bands is given in Table 3.

3.2. *48 mHz QPO*

A 48 mHz QPO was detected in all of our optical, ultraviolet, and X-ray data, and is clearly visible in Figure 2 and 3. This feature has been previously detected at both X-ray and optical wavelengths (Shinoda et al. 1990; Chakrabarty 1998). Its centroid and width ($Q \approx 4$) were both quite stable across all our observations. In the ultraviolet data, individual cycles of the QPO were visible. The fractional rms amplitude of the X-ray QPO was in the 12–15% range, while the amplitude of the simultaneous optical QPO was 3–4%. The optical/X-ray amplitude ratio for this QPO had a stable value of $\approx 30\%$ over all the simultaneous observations. The NUV/X-ray and FUV/X-ray amplitude ratios were significantly lower and higher, respectively. A summary of the 48 mHz QPO amplitude in the various observations is given in Table 3.

3.3. *130 mHz pulsation and related features*

A coherent pulsation near 130.4 mHz, corresponding to the neutron star spin frequency (which evolves on a time scale of $|\nu/\dot{\nu}| \approx 5000$ yr; Chakrabarty et al. 1997), was detected in all of the X-ray and ultraviolet observations, as well as every optical observation with sufficiently fast sampling. This optical pulsation has been well studied previously and was also accompanied by the usual symmetric sidelobe structure ($[\sin^2 \pi\nu/(\pi\nu)^2]$; see, e.g., van der Klis 1989) due to the finite data length. In addition, the 260.8 mHz second harmonic[5] was also detected in all of the X-ray data and some of the optical/UV observations. Note that this frequency slightly exceeds the 250 mHz Nyquist frequency for the 2 s optical data, causing the harmonic to actually be detected at an aliased frequency

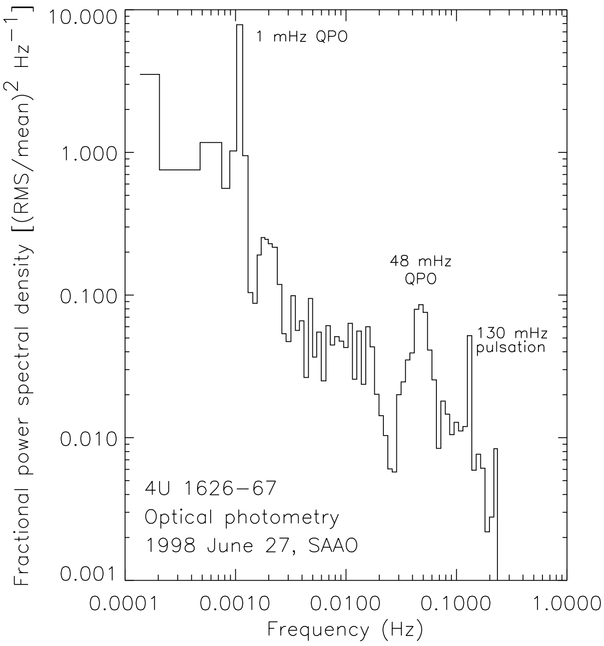

FIG. 2.— Fourier power density spectrum of an 8.1-hr white light observation of 4U 1626–67 on 1998 June 27, normalized relative to the mean source power. A 1 mHz QPO, as well as a previously known 48 mHz QPO and 130 mHz pulsation, are visible in the data.

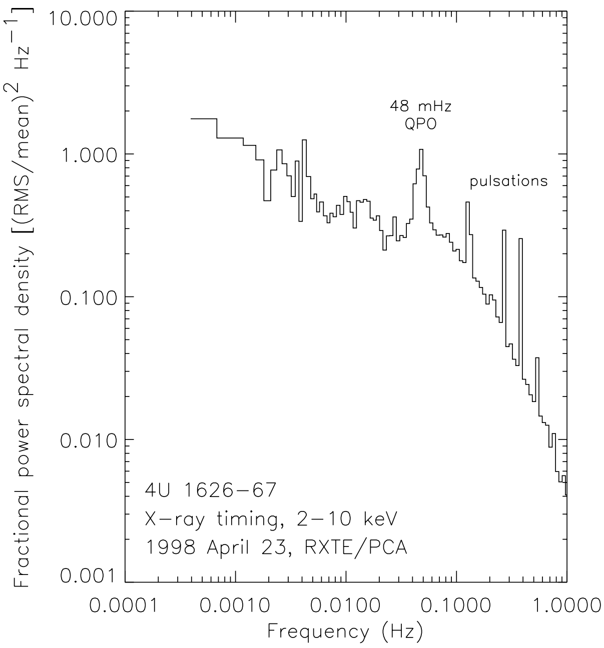

FIG. 3.— Fourier power density spectrum of an 2.3-hr 2–10 keV *RXTE*/PCA observation of 4U 1626–67 on 1998 Apr 23, normalized relative to the mean source power. This observation is simultaneous with the *HST* UV observations shown in Figure 1, both of which show a 1 mHz QPO clearly. The 1 mHz QPO is undetected in the X-ray data, although the previously known 48 mHz QPO and several harmonics of the 130 mHz pulsation are clearly visible.

[5] We have adopted the convention that $m\nu$ is the frequency of the mth harmonic for a fundamental frequency ν.

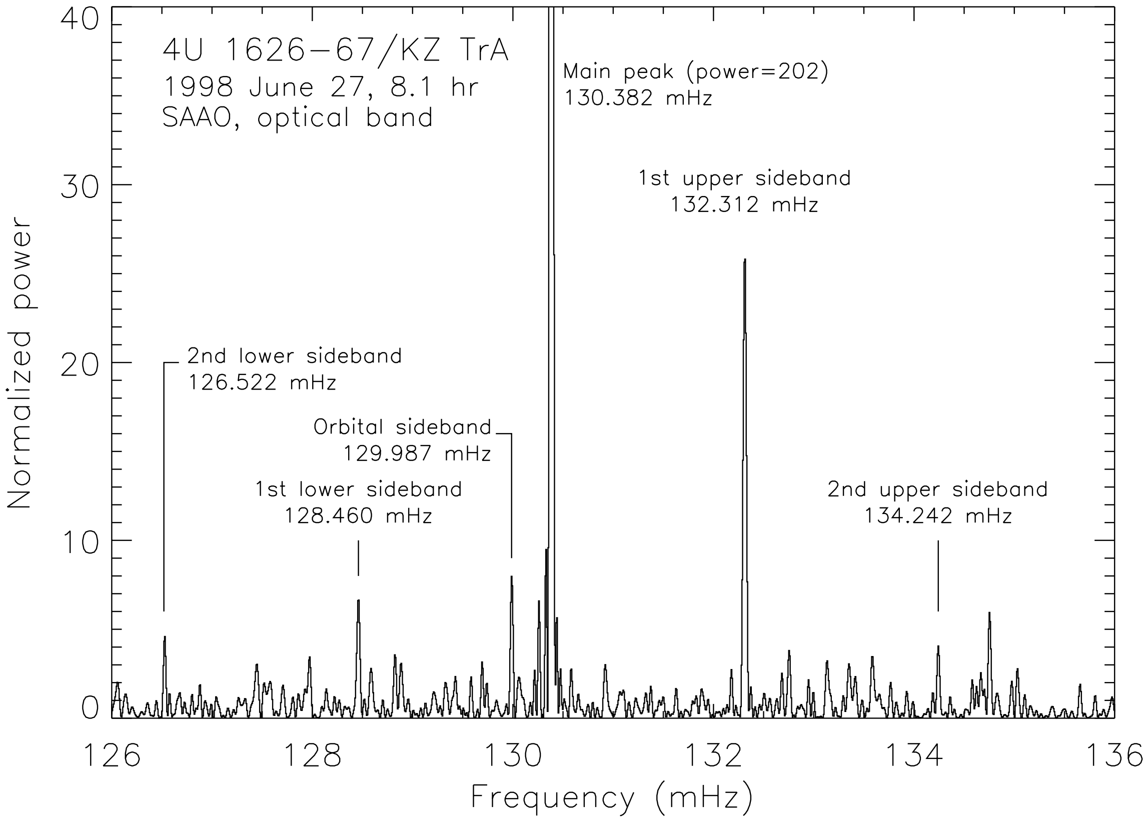

FIG. 4.— Expanded view of an oversampled unit-normalized Fourier power spectrum of the 8.1 hr white light observation of 4U 1626–67 on 1998 June 27, centered on the 130.382 mHz pulsation. The previously known orbital lower sideband ($\Delta\nu$ = 0.395 mHz) is shown, as well as two pairs of previously unknown equispaced lower and upper sidebands with $\Delta\nu$ = 1.93 mHz.

$\nu_{\rm alias} = \nu_{\rm Nyquist} - (\nu \bmod \nu_{\rm Nyquist}) = 239.2$ mHz. Binning effects cause aliased signal amplitudes in this region to be suppressed by a factor of 0.61 relative to the true signal amplitude (see, e.g., Leahy et al. 1983).

In several of the optical/UV observations, the 130.4 mHz pulsation is accompanied by a lower frequency sideband with a separation of 0.395(5) mHz. This feature, which was first reported by Middleditch et al. (1981) and later confirmed by Chakrabarty (1998), is understood as reprocessing from the surface of the mass donor star. The downward shift relative to the main pulsation frequency implies a prograde 42 min binary orbit for the system. This is the first time that the orbital feature has been confirmed by an instrument other than the ASCAP single-channel photometer at the Cerro Tololo Inter-American Observatory.

We computed an oversampled power spectrum of the longest optical observation (1998 June 27) in order to study the timing properties of the coherent pulsations in more detail. The oversampled power spectrum in this frequency region is shown in Figure 4. Besides the main pulsation [130.382(1) mHz] and the orbital sideband [129.987(5) mHz], two additional pairs of sidebands are also detected. These sidebands are identically spaced around the main pulsation at frequencies $\nu_{\rm spin} \pm \Delta\nu$ and $\nu_{\rm spin} \pm 2\Delta\nu$ with $\Delta\nu = 1.93(1)$ mHz. In the first sideband pair, the rms amplitude of the upper sideband is twice that of the lower sideband, but the second pair of sidebands have equal strength. A single pair of sidebands with the same frequency separation are also detected around the (aliased) second harmonic of the main pulsation. These sidebands are also asymmetric in amplitude, but it is the (apparent) lower sideband which is stronger than the upper sideband. However, due to aliasing, the (true) higher frequency sideband actually appears as a *lower* sideband, and vice versa, so the sense of the amplitude asymmetry is in fact the same as in the first sidebands of the fundamental. These 1.93 mHz sideband pairs are not detected in any of the other optical, UV, or X-ray observations[6] However, we note that the other optical/UV observations were of shorter duration (and generally less sensitive), while the X-ray observations were measuring direct rather than reprocessed emission.

A summary of the rms amplitudes of the coherent pulsations and associated sidebands in each of the various observations is given in Table 4.

4. DISCUSSION

We have identified several persistent, distinct quasi-periodic and periodic oscillations in the optical and ultraviolet flux from 4U 1626–67. Some of these oscillations (the 130 mHz pulsation and its harmonic, as well as the 48 mHz QPO) are also present in simultaneous X-ray data. This is consistent with

[6] Sideband pairs with unequal amplitudes have been previously observed around the X-ray pulsation (Kommers et al. 1998). However, these sidebands are spaced by the 48 mHz QPO frequency.

TABLE 4

FRACTIONAL RMS AMPLITUDE OF COHERENT PULSATIONS

		Fundamental						Second harmonic		
Date	Band	Main peak 130.4 mHz (%)	1st lower sideband 128.5 mHz (%)	1st upper sideband 132.3 mHz (%)	Orbital sideband 130.0 mHz (%)	2nd lower sideband 126.5 mHz (%)	2nd upper sideband 134.2 mHz (%)	Main peak 260.7 mHz (%)	Lower sideband 258.8 mHz (%)	Upper sideband 262.3 mHz (%)
1998 Apr 23	NUV	0.65	<0.3	<0.1	0.47	<0.3	<0.3	0.37	<0.2	<0.3
1998 Apr 23	FUV	1.3	<0.5	<0.5	<0.5	<0.5	<0.5	<1.5	<0.5	<0.5
1998 Apr 23	X-ray	8.4	<0.5	<0.5	<0.7	<0.5	<0.5	7.8	<0.6	<0.5
1998 Jun 27	Optical	2.8	0.5	1.0	0.5	0.3	0.3	0.7[a]	0.4[a]	0.7[a]
1998 Jun 27	X-ray	8.1	<0.6	<0.5	<0.5	<0.5	<0.5	9.5	1.1?	1.6?
1998 Jun 28	Optical	3.0	<0.1	<0.2	0.8	<0.2	<0.2	1.2[a]	<0.2[a]	<0.2[a]
1998 Jun 28	X-ray	8.8	<0.6	<1.2	<2.0	<1.0	<1.0	9.3	<0.9	<0.5
1998 Jun 29	Optical	2.7	<0.3	<0.2	0.8	<0.3	<0.3	1.1[a]	<0.1[a]	<0.2[a]
1998 Jun 29	X-ray	7.7	<0.7	<0.6	<1.8	<1.0	<1.0	8.9	<0.5	<1.2

[a] Detected at aliased frequency $\nu_{\rm alias} = \nu_{\rm Nyquist} - (\nu \bmod \nu_{\rm Nyquist})$. The true signal amplitude is higher by a factor of 1.64 due to attenuation by binning (see text).

the optical/UV variability arising from the reprocessing of variable X-ray emission (which itself arises from accretion onto the pulsar) in the accretion disk, as recognized previously (Chester 1979; McClintock et al. 1980; Chakrabarty 1998). The 0.395 mHz orbital lower sideband of the 130 mHz optical pulsation has no X-ray counterpart, but is nevertheless understood as reprocessing from the surface of the pulsar's binary companion (Middleditch et al. 1981).

However, the 1 mHz QPO, while strong in the optical/UV emission, is undetected in simultaneous X-ray data, and thus cannot easily be attributed to reprocessing of variable X-ray illumination. The feature is fairly narrow in frequency, unlike the broader mHz ultraviolet QPOs recently reported in the LMXB pulsar Her X-1 by Boroson et al. (2000). The time scale of the 1 mHz QPO is similar to the flaring time-scale seen in simultaneous X-ray and optical data during the 1970s and 1980s (Joss et al. 1978; McClintock et al. 1980; Li et al. 1980). However, those events were abrupt, well-defined flares occuring on $\sim$1000 s time scales and lasting $\sim$500 s, with flux enhancements of (1.3–3)$\times$ the quiescent level; they were also simultaneously observed in both the X-ray and optical bands. This is quite unlike the quasi-sinusoidal optical/UV modulations we report here. Interestingly, the $\sim$1000 s X-ray/optical flares have not been seen in any data acquired since 1990 (Chakrabarty et al. 2001, in preparation), possibly related to the abrupt 1990 change in the pulsar's accretion torque state and X-ray spectrum (Chakrabarty et al. 1997). In any case, the optical flares were consistent with reprocessing of X-ray flares by the accretion disk.

We suggest that the 1 mHz QPO modulation arises from a purely geometric effect: a "warping" of the accretion disk, wherein the tilt angle of the normal to the local disk surface varies with azimuth. In this case, we would expect the flux of reprocessed emission visible along our line of sight to vary as the reprocessing geometry evolves due to the warp. We note that the 1 mHz QPO is strongest in the FUV band; emission in this band most likely originates in the inner accretion disk, which is truncated by the pulsar magnetosphere near the pulsar's corotation radius $r_{\rm co} = 6.5\times10^8$ cm (see Chakrabarty 1998). The weaker amplitude of the QPO in the optical band suggests that the warp primarily affects the inner disk. As such, we might expect this phenomenon to be difficult to detect in high-inclination binaries, where shadowing by the outer disk may be a strong effect. It is thus interesting to note that 4U 1626–67 is a very low-inclination (nearly face-on) binary (e.g., Levine et al. 1988; Chakrabarty 1998). A test of our warped disk hypothesis could be made by observing the 1 mHz QPO simultaneously in the UV and the optical, since this ought to allow a measurement of the geometry of the warp over the entire disk.

The possibility of accretion disk warping has attracted considerable recent theoretical interest. Several authors have shown that if an accretion disk is subject to sufficiently strong central irradiation, then it is unstable to warping (Petterson 1977; Pringle 1996; Maloney et al. 1996). Pringle (1996) showed that even an initially flat disk is unstable to warping, and Wijers & Pringle (1999) suggested that warping should be generic in irradiated disks, but Ogilvie & Dubus (2001) argue that warping will only occur under a limited range of conditions. We note, however, that in the Pringle instability the warp is strongest in the outer disk and has time scales of order days to weeks; it is therefore unclear whether this model can explain our mHz QPO. An alternative disk warping mechanism based on magnetic torques acting on the inner disk has also been proposed, and may be the disk-magnetosphere interaction in the source (Lai 1999; Terquem & Papaloizou 2000).

The origin of the coherent $\Delta\nu = 1.93$ mHz optical sidebands is unclear. Although the separation frequency is of the same order as the frequency of the 1 mHz QPO, the sidebands are very narrow in frequency, unlike the QPO. Warner (1986, 1995) has shown that optical reprocessing in intermediate polars (accreting magnetic white dwarfs, analogous to the X-ray pulsars) can give rise to pairs of sidebands around the spin frequency, spaced by the binary orbital frequency. It is possible that 518 s (1/1.93 mHz) is the orbital period, rather than the previously inferred 42 min ($\approx$ 2500 s). However, we regard this as unlikely for three reasons. First, the long-term stability of the 0.4 mHz lower sideband (Middleditch et al. 1981; Chakrabarty 1998) is strong evidence for a 42 min orbit. Second, the optical/UV spectrum of 4U 1626–67 is best fit with an X-ray heated accretion disk whose outer radius is $\approx 2\times10^{10}$ cm (Wang & Chakrabarty 2001), which is consistent with a 42 min binary but too large for a 518 s binary. Finally, a 518 s binary is likely below the minimum orbital period ($\sim$10 min) possible for a binary with a hydrogen-depleted secondary (analogous to the 80 min minimum for hydrogen-rich secondaries; see Paczynski &

Sienkiewicz 1981 and Nelson, Rappaport, & Joss 1986).

In some ways, the 1.93 mHz sidebands are reminiscent of the "superhump" phenomena observed in the SU UMa class of dwarf novae (see Osaki 1996 and references therein). During infrequent "superoutbursts", these sources show periodic photometric variability at periods a few percent longer than the binary period. This variability has been interpreted in terms of a tidally-driven eccentric instability in the accretion disk, first proposed by Whitehurst (1988). This instability evidently requires extreme mass ratios (i.e., a very low-mass donor, as in 4U 1626–67). In this picture, the superhump period arises from a beat between the binary period and the the slow precession frequency of an eccentric disk. Although it is difficult to reconcile this scenario with the 42-min binary orbit inferred for 4U 1626–67, it is possible that 1.93 mHz represents a precession frequency in the accretion disk that is modulating the optical reprocessing. Alternatively, the sidebands may arise from reprocessing in some sort of asymmetric feature orbiting in the disk. The 1.93 mHz separation corresponds to a Keplerian radius of $\approx 1 \times 10^{10}$ cm, roughly one-third the binary separation. Such an asymmetry might be related to warping of the disk as well.

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